Investigation of nonlinear bulk viscoelasticity in complex media using dynamic acoustoelasticity

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C.Trarieux[1], S. Callé[2], H. Moreschi[1], M. Defontaine[1]

[1]Rheawave SAS, Bâtiment Vialle, 10 bd Tonnellé, 37032 Tours, France

[2] Université François-Rabelais, INSERM Imagerie et Cerveau UMR U930, 10 bd Tonnellé, 37032 Tours, France

E-mail : chloe.trarieux@rheawave.com

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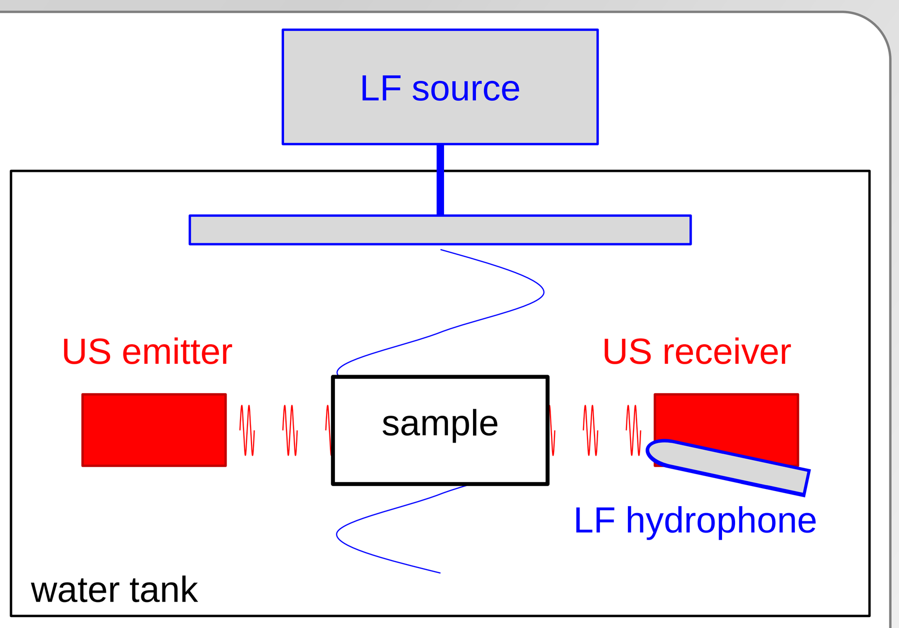
. Acoustic rheology
. Nonlinear viscoelasticity

Introduction

- Few tools have been developed for industrial quality control of textures. The use of non-contact techniques, based on acoustic waves, offers obvious advantages in food-processing or cosmetics industries : health & safety, non-destructive testing, continuous inline measurement.
- The Dynamic AcoustoElastic Testing (DAET) assesses the nonlinear viscoelastic properties of materials in response to a bulk compression/expansion stress. In this study, we present several applications of DAET method in complex media.

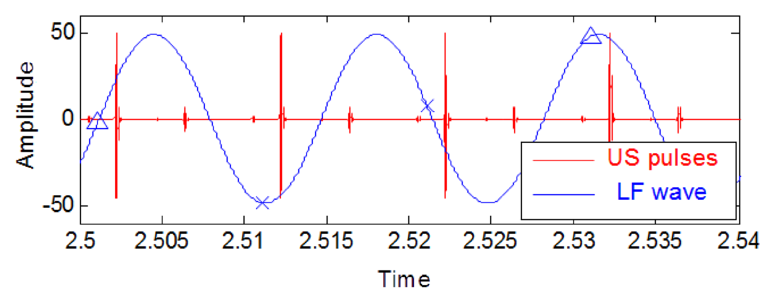
DAET method

- Interaction between two acoustic waves :
  - Low-frequency sinusoidal wave (LF, 4kHz) to successively compress and expand the medium,
  - Ultrasound longitudinal pulses (US, 1 MHz) to probe this medium at different pressure values imposed by the LF wave.

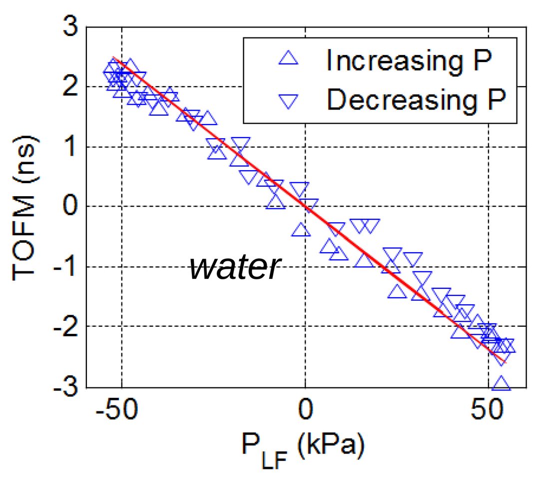


DAET synopsis

- Measurement of the Time of Flight Modulations (TOFM) of the US pulses, induced by the variations of the applied LF pressure: $TOFM = TOF_{P_{LF}} - TOF_0$



Acquired signals



- **DAET diagram:** plot of TOFM as a function of LF pressure

$$\Rightarrow TOFM^* \simeq -\frac{L}{c_0^2}\Delta c^* \simeq -\frac{L}{2\rho_0 c_0^3}\Delta M^*$$

with c the celerity, L the length propagation, ρ the density and $\mathbf{M^* = \rho c^{*2}}$ the complex longitudinal modulus

Nonlinear viscoelastic parameters

- $$M^* = A^* - B^*\varepsilon + C^*\frac{\varepsilon^2}{2} - \ldots$$

$$\Rightarrow \Delta M^* = -B^*\varepsilon + C^*\frac{\varepsilon^2}{2} - \ldots \quad = -(B + j\omega\eta_B)\varepsilon + (C + j\omega\eta_C)\frac{\varepsilon^2}{2} - \ldots$$

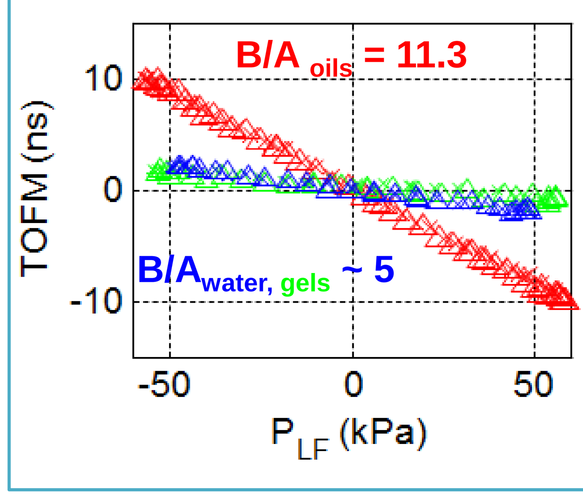
- From the measured TOFM, we identify nonlinear viscoelastic parameters:

$$TOFM = -\frac{L}{2\rho_0 c_0^3}\mathrm{Re}\left\{\left(\frac{B}{A} + j\frac{\omega\eta_B}{A}\right)\Delta P + \left(\frac{C}{A} + j\frac{\omega\eta_C}{A}\right)\frac{\Delta P^2}{2A}\right\}$$

Elastic parameters (B/A, C/A) Viscous parameters ($\omega\eta_B/A$, $\omega\eta_C/A$)

Validation in Fluids

HOMOGENEOUS MEDIA



Water, Carbomer gels, Silicon oils :

- Low values of B* ⇒ homogeneous media

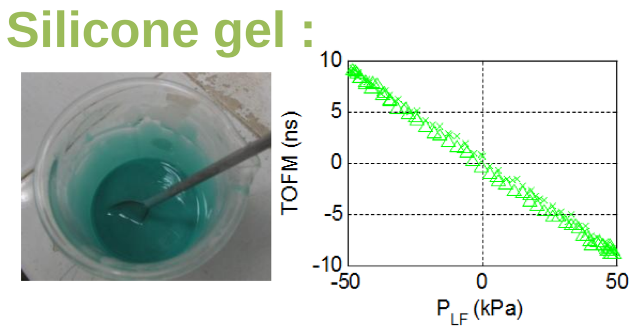
B/A	<15
$\omega\eta_B/A$	<1

- Governed by **fluid nature**

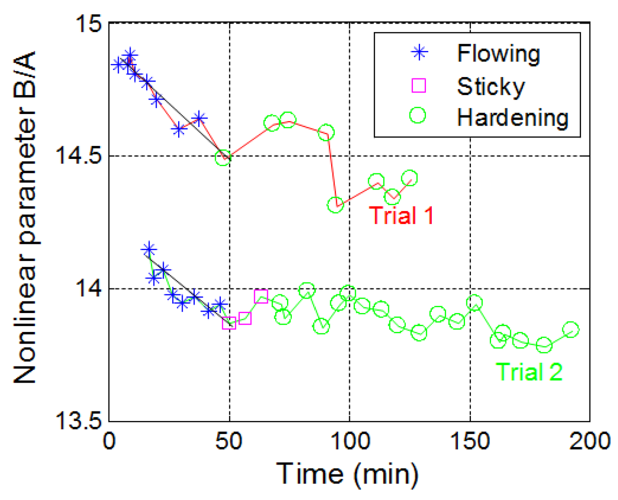
Results in Complex media

POLYMERIZATION

Silicone gel :

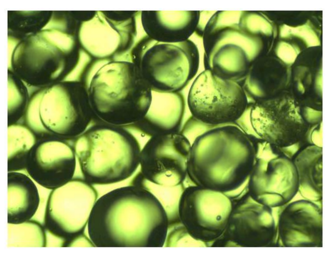


- **Silicon hardening kinetics** :
  ⇒ Gel time determination

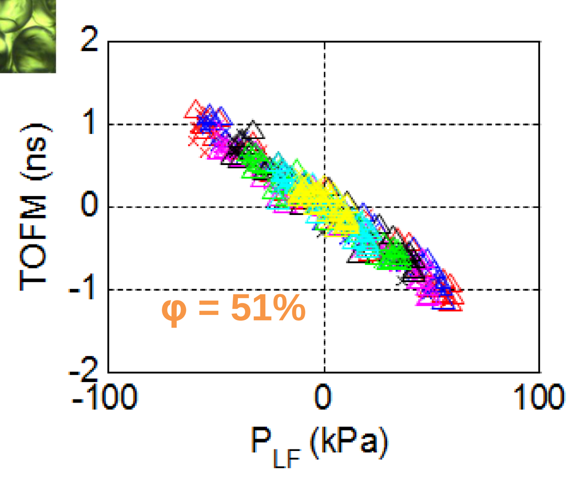


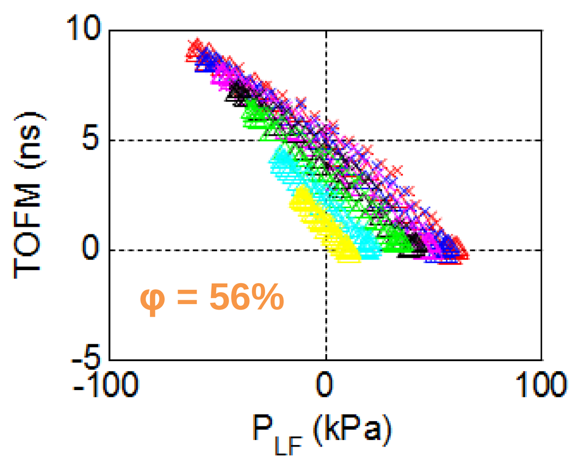
Governed by **chemical bonds**

GRANULAR MEDIA



250 µm glass beads in gelatin :





No beads contact (B*) ⇒ **Beads contact** (B*, C*)

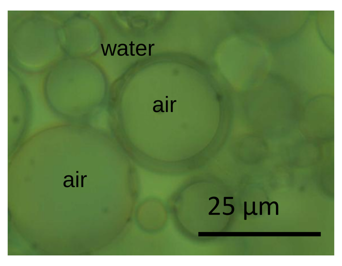
B/A	12,2 ± 0,2
$\omega\eta_B/A$	-0,5 ± 0,7
Offset (ns)	0,0 ±0,1

B/A	68 ± 13
$\omega\eta_B/A$	14 ± 3
C/A ($x10^6$)	2 ± 1
Offset (ns)	3,9 ± 1,1

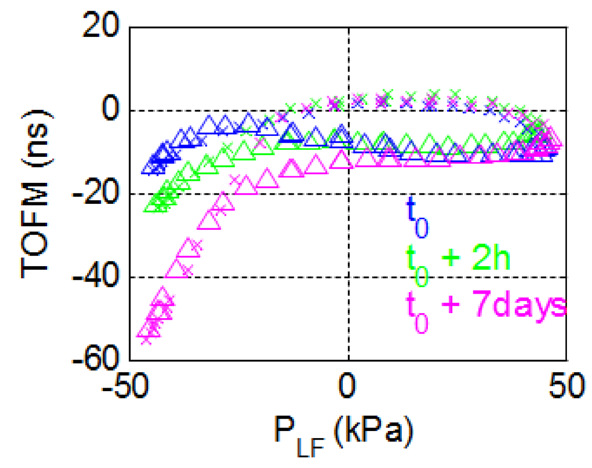
- Sensitivity to a **percolation threshold**

Governed by **beads contact**

AIR-BASED MEDIA

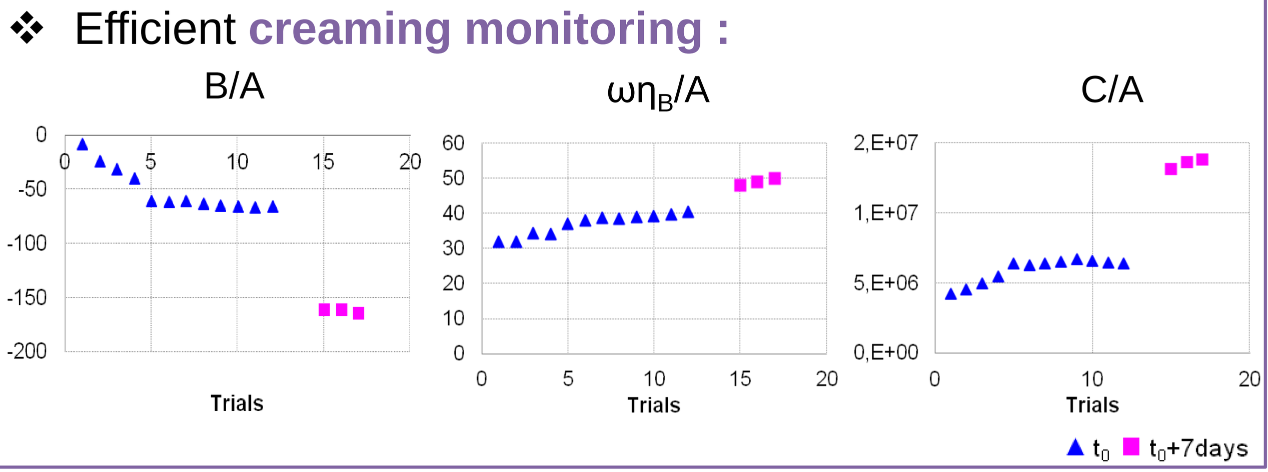


Hollow glass beads in water :



- High values of B*, C* and D*
  ⇒ air presence

- Efficient **creaming monitoring :**



Governed by **air and beads contact**

Conclusion and perspectives

- The DAET method measures with a good reproducibility the variations of the bulk viscoelastic modulus, through the quantification of nonlinear elastic and viscous parameters.
- Homogeneous fluids exhibit classical viscoelastic nonlinearities (1[rst] order B*) and complex media nonclassical viscoelastic nonlinearities (until 3 orders B*, C*, D*).
- This method appears to be an interesting alternative to conventional rheometry, especially for the characterization of these complex fluids.
- A similar work has to be done on the RAM data related to an attenuation of US pulses (thanks to a nonlinear Kramers-Kronig relationship ?…)

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